The Extractive Industries and Society 15 (2023) 101311

Contents lists available at ScienceDirect

The Extractive Industries and Society

journal homepage: www.elsevier.com/locate/exis

Original article

Mapping to explore the challenges and opportunities for reconciling artisanal gem mining and biodiversity conservation

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ARTICLE INFO

Keywords:
Artisanal and small-scale mining
Biodiversity conservation
Madagascar
Formalisation
Protected areas

ABSTRACT

Artisanal and small-scale mining (ASM) provides a vitally important livelihood for millions of people in many low- and middle-income countries. ASM can result in habitat clearance, increased hunting pressure, pollution, and sedimentation of waterways. Consequently, where mineral and biological wealth coincide, there are trade-offs. Here, we combine geological data with four datasets capturing conservation priorities, to evaluate where, and to what extent, mining may impact biodiversity, and to explore opportunities for both to co-exist. We use Madagascar as a case study: a biodiversity hotspot rich in economically important minerals where artisanal gem mining has conflicted with biodiversity conservation. We identify areas of Madagascar most likely to host primary deposits of gems and find that 11%–14% of the most important area for biodiversity on the island could host primary gem deposits. However, we also identify 7 million hectares (80%) of potentially prospective land which is *outside* of these areas. Establishing decentralised, community-managed zones for licensed ASM in such areas could help to incentivise formalisation and minimise social and environmental trade-offs. Our mapping approach could be applied in other countries to encourage the establishment of designated zones for ASM in places where mining does not conflict with conservation.

1. Introduction

Artisanal and small-scale mining (ASM) has expanded rapidly in recent decades to become a major livelihood in many low- and middle-income countries, involving an estimated 45 million people in 2020 (World Bank, 2020). Much ASM occurs in countries which are resource-rich but economically poor (IGF, 2017), where ASM can contribute towards poverty alleviation by providing alternative or additional means of income generation, particularly in rural areas with few other options (Hirons, 2020). Engaging in ASM can help to buffer shocks, sustain agricultural livelihoods, and raise funds for investments which are otherwise unattainable (Hilson and Garforth, 2012; Hilson and Maconachie, 2020). However, many of these places are also hotspots for biodiversity (e.g. the Amazon, East Africa, Indonesia and Madagascar), where ASM's contributions to development may involve significant environmental trade-offs (Villegas et al., 2012; Hirons, 2020).

ASM is a labour-intensive and sometimes risky form of mineral extraction and processing characterised by limited use of machinery (Hilson and McQuilken, 2014; Lahiri-Dutt, 2018). It requires little capital investment and, as such, is highly accessible (Yakovleva, 2007). ASM operates mostly outside of the legal economy and formal regulatory structures, and this informality can lead to environmental degradation, poor health and safety, crime and corruption (Duffy, 2007; Verbrugge, 2015; Smith et al., 2016; Gerety, 2017). Historically, much of the narrative around ASM has focussed on these negative social and environmental impacts (Hilson and McQuilken, 2014). However, in recent decades there has been growing recognition of the key role that ASM plays in poverty alleviation and it's potential to contribute towards development (Hilson and McQuilken, 2014). This has led to growing calls to formalise the sector to improve conditions, increase efficiency and to mitigate the environmental impacts (Hilson et al., 2017).

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https://doi.org/10.1016/j.exis.2023.101311
Received 12 January 2023; Received in revised form 7 July 2023; Accepted 7 July 2023
Available online 12 July 2023

1.1. The environmental impacts of ASM

Direct environmental impacts of ASM include; deforestation and habitat loss (Espejo et al., 2018; Macháček, 2019; Álvarez-Berríos et al., 2021; Barenblitt et al., 2021; Laing and Moonsammy, 2021); soil disturbance leading to the sedimentation of waterways, impacting freshwater biodiversity, water quality and flow (Hollestelle, 2012; Lobo et al., 2016); and chemical pollution (Nkuba et al., 2022). Mercury contamination from artisanal gold mining is a major problem in many countries (although not currently Madagascar, Klein 2022b), with serious implications for both human (Gibb and O'Leary, 2014) and ecosystem (Boening, 2000) health. ASM can also generate substantial indirect impacts, particularly when it occurs at scale in remote areas (Villegas et al., 2012; Hirons, 2020). Miners need fuel and wood for constructing shelters and mineshaft supports, resulting in tree felling (Schure et al., 2011; Macháček, 2019; Nkuba et al., 2022). A growth in local demand for food can spur land conversion for agriculture (Maconachie and Binns, 2007) and increase hunting of threatened species (Hollestelle, 2012; Spira et al., 2019). Artisanal mining can open up remote frontiers to other forms of resource extraction and miners may turn to other, more environmentally damaging forms of income generation, such as charcoal production, as the value of finds decreases (Villegas et al., 2012; Kinyondo and Huggins, 2021; Zhu and Klein, 2022). When hundreds, or even thousands of people converge upon a remote, biodiverse area (such as a Protected Area) to mine, the collective impact on biodiversity can be severe (Villegas et al., 2012; Asner and Tupayachi, 2017). Consequently, where the world's mineral and biological wealth coincide, there can be substantial trade-offs.

1.2. Madagascar: a biological and mineral hotspot

Madagascar is internationally renowned for its biodiversity (Myers et al., 2000), but the island is also incredibly rich in economic minerals (Yager, 2019). Madagascar is a poor country and is unsurprisingly using its mineral wealth to support development (EDBM, 2021). While the government has been promoting expansion of the formal mining sector (Canavesio, 2014), ASM has grown rapidly over the past 30 years to become the second most important rural livelihood after agriculture, involving hundreds of thousands of people and indirectly supporting an estimated 2.5 million more in downstream industries (World Bank, 2010; Hilson, 2016). Most ASM targets gold and high-value gemstones, such as ruby and sapphire (Cartier, 2009; Cook and Healy, 2012).

Both Madagascar's mineral and biological wealth stem from a dynamic geological history involving the formation and break-up of supercontinents (Pezzotta, 2001; Richard, 2022). Most of Madagascar's gem deposits, as well as those of neighbouring Mozambique, Tanzania and Kenya, were formed 650 – 500 Ma during the East African and Kuungan orogenies (Rakotondrazafy et al., 2008; Giuliani et al., 2020) when much of Madagascar, and subsequently India, collided with East Africa during the assembly of Gondwana (Fritz et al., 2013). The eastern two-thirds of Madagascar comprises a mosaic of Precambrian crustal blocks that were finally assembled during this period (Fig. S1; (Tucker et al., 2014). Continental convergence led to regional metamorphism and intrusive magmatism which produced the high temperatures, pressures, and fluids necessary for the formation of gems. Understanding the geological conditions (i.e. the temperatures, pressures and chemical compositions of rocks) required for gem formation allows us to identify which areas of Madagascar are most likely to be prospective for gems.

Madagascar's gem deposits remained mostly untapped until the discovery of sapphires in the far south of the island in 1992 (Cook and Healy, 2012). This initiated a cascade of discoveries across the island, each attracting a rush of migrant miners, sometimes numbering in the tens of thousands (Canavesio and Pardieu, 2019). Since then ruby and sapphire have been found in numerous locations across the island (Rakotondrazafy et al., 2008), making Madagascar a leading global producer of high-quality gems (Shor and Weldon, 2009; Giuliani et al., 2020).

1.3. Environmental and social trade-offs of ASM in Madagascar

People engage in artisanal mining in Madagascar for a variety of reasons: to meet basic needs; diversify livelihoods and reduce risk; raise income to invest in business, housing or education; as a last line of defence against destitution; or to spend on luxury goods (Walsh, 2003; Cartier, 2009; Lawson, 2018). Artisanal mining can also facilitate female empowerment (Lawson, 2018). As such, ASM plays a vitally important role supporting the lives and livelihoods of millions of people across Madagascar, but it can also generate negative social and environmental impacts (Walsh, 2003; Duffy, 2007; Canavesio, 2009; Cook and Healy, 2012; Cabeza et al., 2019). ASM for gems has impacted important areas for biodiversity as the following examples illustrate.

In 1996, sapphires were discovered near the village of Ambondromifehy in the north-west and within two years an estimated 14,000 people were mining in the area, including within the adjacent Ankarana Special Reserve (Walsh, 2003; Tilghman et al., 2007). Miners felled trees to clear the land for mining and to obtain wood for fuel and mine supports (Cook and Healy, 2012). Repeated disturbance displaced wildlife and impeded forest regeneration. The number of miners operating within the reserve and the inability of the authorities to evict them, exacerbated by long-standing conflicts over resources, created de-facto conditions of open access in the northern part of the reserve (Baker-Médard, 2012). This enabled an increase in other, more destructive forms of resource use, namely charcoal production and harvesting of precious woods (Tilghman et al., 2007; Cook and Healy, 2012).

The giant Ilakaka sapphire rush which started in 1998 has affected an extensive area of south-west Madagascar (Fig. 1; Canavesio, 2009). Whilst much of this region comprises species-poor savannah, ASM has impacted highly biodiverse dry forests within Zombitse-Vohibasia National Park (Tilghman et al., 2007; Cook and Healy, 2012). In the early 2000s, forest within and around the protected area were cleared for agriculture to meet the growing demand for food from the burgeoning mining population (Cook and Healy, 2012). Then, in 2003, sapphires were discovered in the buffer zone around the protected area and mining gradually spread into the interior (Tilghman et al., 2007). ASM has, directly and indirectly, caused substantial forest loss within Zombitse-Vohibasia National Park, as well as increased soil erosion and sedimentation of waterways (Cook and Healy, 2012).

1.4. This study

We evaluate where, and to what extent, gem mining could occur within other important areas for biodiversity across Madagascar, and explore ways to minimise trade-offs between ASM, rural livelihoods and biodiversity conservation. We quantify the spatial overlap between the potential distribution of primary gem deposits and four datasets capturing biodiversity conservation priorities. We focus on ruby, sapphire and emerald as these constitute Madagascar's largest gem exports by quantity and value (Cartier, 2009). Using a simplified mineral systems approach we identify areas most likely to host primary ruby, sapphire and emerald deposits based on the underlying geology, and validate the resulting map against a database we compiled of known gem deposits. Next, we explore the spatial overlap with areas of importance for biodiversity; Key Biodiversity Areas (Birdlife International, 2021); Conservation Priority Areas, which capture the distribution of many endemic species (Kremen et al., 2008); protected areas (Rebioma, 2017); and natural forests (Hansen et al., 2013).

Fig. 1. Ilakaka before (left) and ten years after (right) the discovery of sapphires which triggered Madagascar's largest gem rush and transformed the area into a gem mining and trading hub. © Pierrot Men.

2. Methods

2.1. *Identifying areas potentially prospective for gemstones*

Potentially prospective refers to areas with the right geological conditions for the formation of gemstones at the broad-scale. We use the qualifier 'potentially' because; a) small-scale variation means the right conditions will not be present across the entire area, and b) ground truthing and geological exploration is necessary to determine whether an area is truly prospective (i.e. *likely* to contain economic deposits of gemstones).

We use a top-down, mineral systems approach (Wyborn et al., 1994) to identify broad areas potentially prospective for primary ruby, sapphire and emerald deposits based on the critical geological processes and lithologies required for formation. This technique was designed to aid targeting of mineral exploration by identifying new prospective areas at larger scales (Hagemann et al., 2016). The focus on large-scale processes of mineralisation, which are often generic, can enable the identification of areas prospective for multiple minerals, and avoids limitations in the availability of high-resolution data needed for traditional targeting methods (e.g. deposit models; Hagemann et al., 2016)

A mineral systems approach requires an understanding of the geological processes and conditions in which the specific minerals are formed. Ruby and sapphire are gem-quality variants of the mineral corundum (Al_2O_3) and typically occur in rocks which are aluminium-rich and silica-poor, and have been metamorphosed at moderate pressures and relatively high temperatures (Simonet et al., 2008; Giuliani et al., 2020). Corundum formation often requires the circulation of a fluid to supply aluminium or other trace elements and remove silica from the host rock, via diffusion along geochemical gradients (Simonet et al., 2008; Giuliani et al., 2020). Emerald is green gem-quality beryl ($Be_2Al_2Si_6O^{18}$) and requires beryllium and trace amounts of chromium and/or vanadium to form. Beryllium is rare in the upper crust and is typically supplied through the intrusion of magma, or by fluids circulating from depth (Giuliani et al., 2019). As such, emeralds are usually associated with intrusive granites, pegmatites or shear zones (zones of rock with enhanced permeability which act as fluid conduits) intersecting chromium-rich rocks (Giuliani et al., 2019). See Supplementary Information for more details.

Our analysis is restricted to primary deposits; those where the gems have not been significantly affected by processes (i.e. erosion and deposition) at the Earth's surface and remain in-situ in the host rock. Secondary deposits are those where gems have been removed from the host rock by erosion and weathering and deposited downslope or within contemporary or paleo river systems. We have topographic data that would enable us to map contemporary river systems, but it is more challenging to map paleo river systems (e.g. within the sedimentary rocks of western Madagascar) and data for these do not exist at a consistent scale across Madagascar. Therefore, as we could not comprehensively assess the potential distribution of secondary deposits, we chose not to include these in our identification of potentially prospective areas.

In Madagascar, the critical large-scale geological processes required for gem formation include: 1) regional metamorphism and magmatism associated with the East African and Kuungan orogenies (Rakotondrazafy et al., 2008; Giuliani et al., 2020); 2) presence of key lithologies in which gems are likely to have formed; notably metamorphosed mafic-ultramafic rocks, low-silica sedimentary rocks such as carbonates, and alkaline volcanic rocks that may contain gems transported from depth (Giuliani et al., 2019, 2020); and 3) major km-scale areas of significant fluid flow, which are typically mapped as shear zones (see Supplementary Information).

The first critical process, regional metamorphism and magmatism, has occurred throughout much of the island's Precambrian basement, excluding the Antongil domain (BGS-USGS-GLW, 2008; Schofield et al., 2010; Fritz et al., 2013). In order to map the other two critical factors, we used the Geological Map of Madagascar at the 1: 1,000,000 scale (Roig et al., 2012) to identify: (a) major shear zones, and (b) geological units with prospective lithologies (marble, mafic-ultramafic rocks, aluminous metasedimentary rocks, skarns, alkaline volcanic rocks) based on the classifications of Giuliani et al. (2020; Table S1). Shear zones can introduce fluids bearing elements such as beryllium and aluminium which can lead to metasomatism of the rocks within and around the shear zones (Giuliani et al., 2020). However, these rocks must be of a suitable lithology for ruby, sapphire, or emerald to form. Therefore, we only selected shear zones which at some point intersect our selected geological units, which are all silica-poor. Since many of Madagascar's major shear zones are associated with metavolcanics and metasedimentary rocks, most are considered prospective.

2.2. *Geological data*

The 1:1 M Geological Map of Madagascar (Roig et al., 2012) was produced by the World Bank funded Projet de Gouvernance de Ressources Minerales (PGRM) which aimed to facilitate development of the mining sector in Madagascar by improving geological knowledge and data availability, governance and management (Cook and Healy, 2012). The map represents the finest resolution, most up-to-date and complete visualisation of Madagascar's geology available.

The geological units in this map represent a simplification of more detailed mapping, and some of these units encompass a range of different lithologies, intimately associated, which cannot be differentiated on a map of this scale (e.g. the basic paragneiss of the Tsaratanana thrust sheet incorporates smaller-scale areas of prospective mafic gneiss and schist which are not shown (Tucker et al., 2014)). In these cases, we took a conservative approach. Where the unit description does not clearly indicate a prospective lithology, and where no corundum or emerald deposits are known from that area, we did not include it in our selection. The units identified thus represent those that are considered most likely to be prospective, but it is still possible that primary gem deposits could be found outside these areas.

We first assessed all the lithological units on the map legend and decided which had the potential to be prospective for gems (Table S1). Then we produced a polyline shapefile of the map which we overlaid on a georeferenced image of the original map and used this to identify and merge polyline segments outlining potentially prospective units. Finally, we digitised the shear zones shown in the raster image and merged with the shapefile of potentially prospective units to form our map of gem potential.

2.3. Validating our map of gem potential against known gem deposits

To provide a first-order validation of our map of gem potential, we compiled a spatial database of known gem deposits (categorised according to whether they are primary or secondary; Table S3) and calculated the distance from each point to the nearest area we identified as potentially prospective (Table S4). Whilst known secondary deposits are not needed to validate our map of *gem* potential, which is targeted towards primary deposits, they were included in this analysis to explore the distance between secondary deposits and potential source rocks.

Known gem deposits in Madagascar were identified from the peer-reviewed and grey literature, and the Mindat website. Rakotondrazafy et al. (2008), Canavesio and Pardieu (2019) and Cook and Healy (2012) provided many key references. We searched the Journal of Gemmology, and Gems and Gemmology using the search term Madagascar for case study analyses of gems from specific locations. We also searched the grey literature to find expedition reports published on the websites of field gemmologists (e.g. Perkins, 2016) and gemmology institutes (e.g. Pardieu and Rakotosaona, 2012). Vincent Pardieu shared the locations of numerous sites he had visited in east and south-west Madagascar.

Mindat (an open spatial database of global mineral occurrences and mine sites compiled by 4500 contributors and verified by a team of 50 experts) was principally used to locate deposits that had been named, but not georeferenced, in other sources. Where available co-ordinates were coarse resolution, or where distance to the nearest settlement was given, we scanned the area on Google Earth to try to visually identify any mine sites. Mindat entries with a margin of error greater than 5 km were not included if no other sources of information could be found.

Our review was not systematic and there are undoubtedly many known gem occurrences in Madagascar which are not reported in the international literature. Therefore, our database should not be considered comprehensive but rather an indicative and informative sample of the distribution of known gem deposits across Madagascar.

2.4. Biodiversity data

Biodiversity is inherently complex and difficult to summarise in a single measure (Purvis and Hector, 2000). To mitigate this, we use four different measures, or proxies, of biodiversity, and calculate the proportion of each which is potentially prospective for gems (Table S2). These datasets are: (1) protected areas (Rebioma, 2017), (2) Key Biodiversity Areas (Birdlife International, 2021), (3) Conservation Priority Areas (Kremen et al., 2008), (4) natural forests (Harper et al., 2007; Hansen et al., 2013; Vieilledent et al., 2018). The overlap with areas of gem potential is not intended to be compared between measures as each measure uses different methodology, biological data, and is subject to different constraints. While there is some spatial overlap between the four layers, there are still considerable differences (Table 1).

Table 1
The extent of spatial overlap between the four biodiversity datasets. Values refer to the percentage of biodiversity layer 1 which is within biodiversity layer 2. E.g. 44% of forests are within protected areas.

	Biodiversity layer 1			
Biodiversity layer 2	**KBA**	**Priority areas**	**Protected areas**	**Forests**
KBA	N/A	46%	74%	55%
Priority Conservation Areas	30%	N/A	31%	28%
Protected areas	55%	36%	N/A	44%
Forests	49%	38%	53%	N/A

Protected areas are established and, in theory, managed to conserve biodiversity. Madagascar's latest cohort of protected areas (granted temporary status in 2005 and formally protected in 2015) was designed to capture important biodiversity features, informed by conservation planning and gap analyses ([*including* Kremen et al., 2008]; Gardner et al., 2018). However, protected areas do not, and cannot, capture all areas important for biodiversity. Therefore, we use three additional datasets to ensure we capture the wider distribution of biodiversity outside the protected area network. Key Biodiversity Areas and Conservation Priority Areas both represent areas of high conservation priority based on species richness and level of threat, incorporating factors such as species range size, endemism, habitat loss and extinction risk (Kremen et al., 2008; IUCN, 2016), but they use different underlying species data. The Key Biodiversity Areas for Madagascar mostly comprise Important Bird Areas and sites identified by the Critical Ecosystem Partnership Fund (CEPF, 2014; pers comm. A Plumptre) using data from a wide range of taxa and expert elicitation. The Conservation Priority areas were defined to maximise the proportional representation of >2000 endemic species from 6 taxonomic groups (ants, butterflies, lemurs, frogs, geckos and plants) on 10% of the land surface (Kremen et al., 2008). Forest is a useful indicator of biodiversity as most terrestrial Malagasy species are forest-dependant (Goodman, 2022). Furthermore, forests also provide essential ecosystem services such as carbon storage, clean water provision, and erosion mitigation, which could be compromised by the environmental impacts of ASM (Laing and Moonsammy, 2021).

To produce a recent map of forest cover we masked the Global Forest Change dataset (Hansen et al., 2013) to a national-scale map of natural forests (excluding plantations) for the year 2000 (Harper et al., 2007; Vieilledent et al., 2018). Following Vieilledent et al. (2018), we then removed all pixels classed as deforested between 2001 and 2020. The resulting map represents forest cover in Madagascar in January 2020.

Protected areas officially classified as marine protected areas and those within a marine portion greater than 80% were removed from the dataset (Table S2). The remaining protected areas were clipped to the boundary of Madagascar. The same procedure was applied to remove marine portions of Key Biodiversity Areas.

2.5. Spatial overlay analysis

Raster overlay was used to calculate the proportion of each biodiversity layer which is potentially prospective for primary ruby, sapphire, or emerald deposits (see Supplementary Information). Following Eklund et al. (2022) we disaggregated the results for forest by forest type (using the biome classification from the Resolve Ecoregions project (Dinerstein et al., 2017)), to evaluate whether certain types of forest (humid, dry or spiny) are more likely to overlap with areas of high gemstone potential (these results are presented in the Supplementary Information, Fig. S2).

We then calculated the percentage of each individual locality (Key Biodiversity Area/Conservation Priority Area/protected area or forest block) which is potentially prospective for gems using Tabulate Intersection on the polygon data (forest and Priority Area layers were first converted from raster, see Supplementary Methods).

2.6. Ethical considerations regarding the presentation of results

Our analysis is a large-scale identification of areas most likely to host primary gem deposits based on the underlying geology. It does not provide detailed locations of where gems will be found (both because of uncertainties associated with the method, and the scale of analysis). However, to avoid signposting potentially prospective areas and generating perverse outcomes, such as encouraging mining within protected areas (Lindenmayer and Scheele, 2017), we have chosen to present our results in a way that obscures identification of these areas (even at the coarse resolution of the image). As such, we only present maps showing the *percentage* of each locality that is potentially prospective for gems, not the *area* within these localities that is potentially prospective (i.e. we do not overlay the map of gem potential on each of the biodiversity layers). This is to avoid highlighting that, for example, the south-west corner of a protected area may contain gems. For this reason, we have also chosen not to make publicly available the detailed spatial data showing the area of gem potential (shown in Fig. 2). However, we

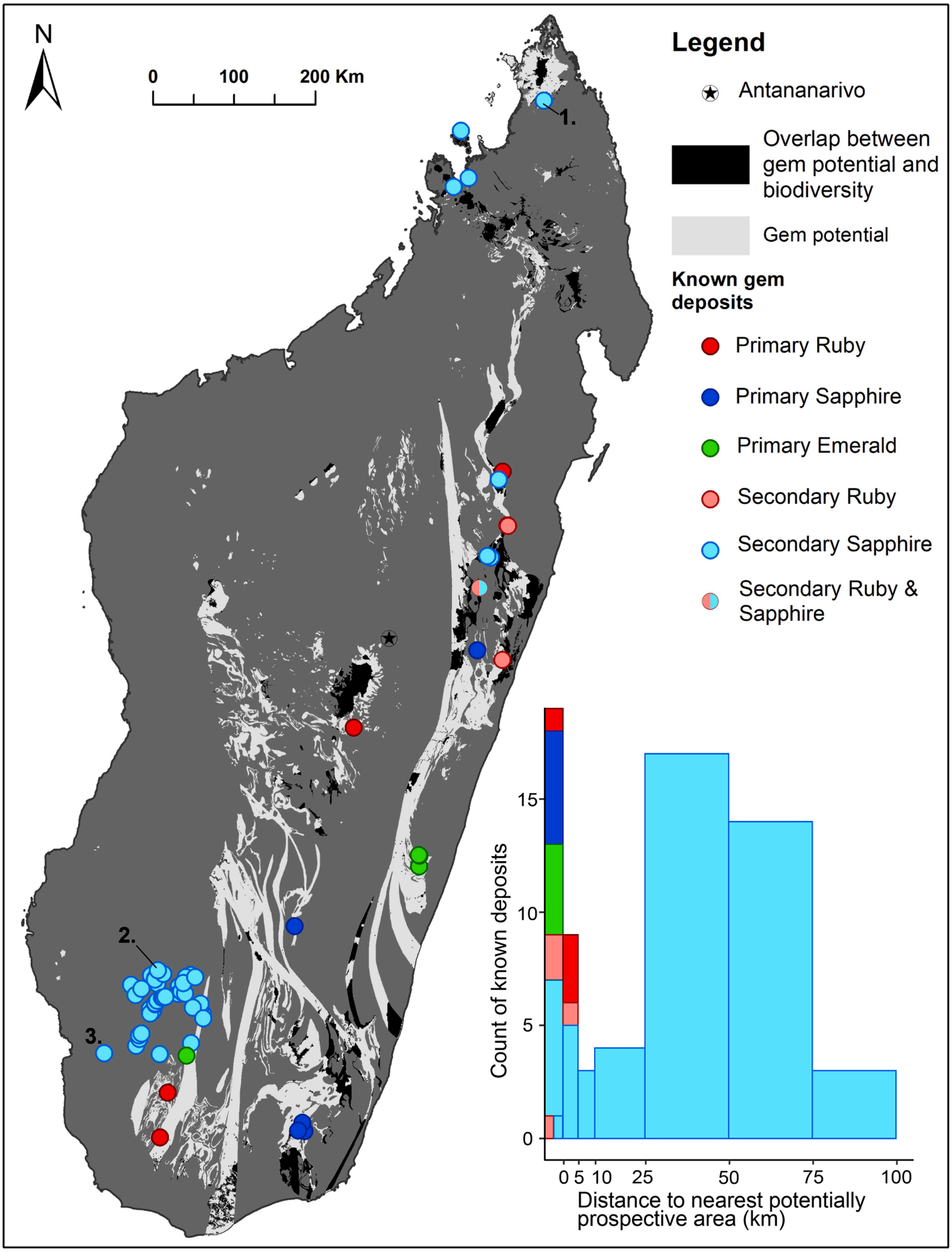

Fig. 2. Our map of gem potential and the location of known gem deposits. Light grey represents the area of gem potential outside of protected areas, Key Biodiversity Areas, Priority Areas, and forests (80%). Potentially prospective land within any of these important areas for biodiversity is shown in black (20%). The histogram shows the frequency distribution of distances between known gem deposits and the nearest polygon we identified as potentially prospective for primary ruby, sapphire or emerald. Points and bars are symbolised according to the type of deposit (i.e. the type of gem and whether the deposit is primary or secondary). The large cluster of secondary sapphire deposits in the south-west are part of the giant Ilakaka deposit. Places named in the text are indicated by numbers: 1 = Ambondromifehy, 2 = mine sites near Zombitse-Vohibasia National Park, 3 = Soabiby.

do publish our spatial database of known gem deposits as these are already known and information is accessible online. We hope that the maps presented below will provide valuable information for policy-makers working in Madagascar on the potential for gem mining to occur in certain areas.

3. Results

The known gem deposits map well onto the areas we identified as potentially prospective for primary gem deposits. Of the 13 primary deposits of ruby, sapphire and emerald in our database, 10 were located within a potentially prospective unit (including all sapphire and emerald deposits) and the other 3 were located within 2 km (Fig. 2; Table S4). This is considered within the margin of error for the geological map due to the limited amount of rock exposure on the ground.

Our results show that approximately 8.8 million hectares of land in Madagascar is potentially prospective for primary deposits of ruby, sapphire or emerald, representing ~15% of the land surface (Fig. 2). 7

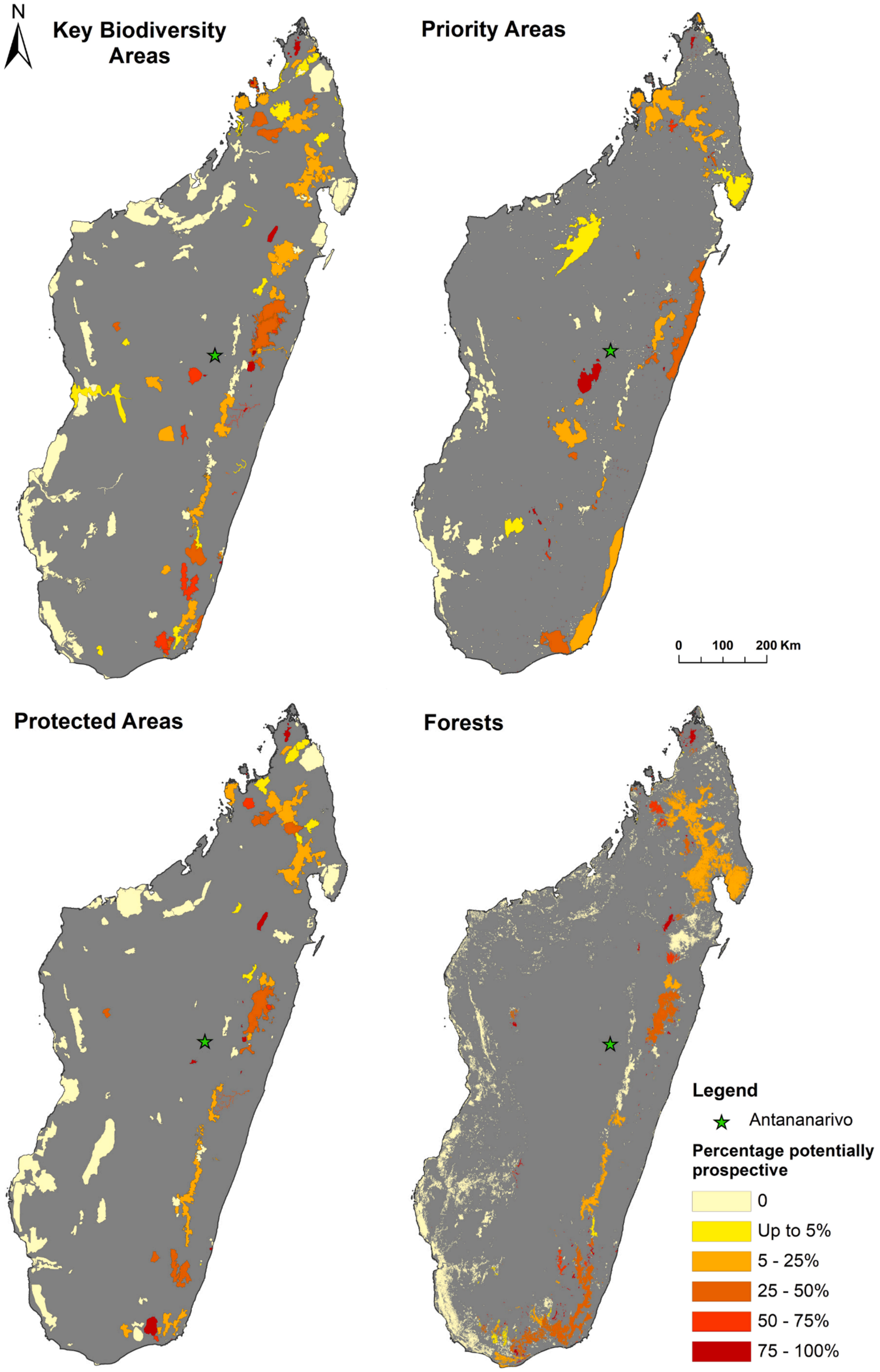

Fig. 3. The percentage of each locality (individual Key Biodiversity Area, Priority Area, protected area and forest block) which is potentially prospective for gems. Darker colours indicate a greater proportion of the area is potentially prospective.

million hectares of this (~80%) occurs *outside* of the most important areas for biodiversity (combining all four biodiversity layers). Potentially prospective areas occur across much of the Precambrian basement in the eastern two-thirds of the island (Fig. 2 and Fig. S1).

We find that 11% of the total terrestrial extent of Key Biodiversity Areas (1017,857 ha), 14% of Priority Areas (839,447 ha), 11% of the terrestrial protected area estate (741,994 ha) and 12% of forested land (991,704 ha) is potentially prospective for primary deposits of ruby, sapphire and emerald (Table S5). A substantial proportion of highly biodiverse, potentially prospective land lies outside of the protected area network: 41% (414,086 ha) of KBA land with gem potential is unprotected, 67% (559,928 ha) of Priority Areas, and 47% (466,479 ha) of forests (Table S5).

Fig. 3 shows the percentage of each individual locality (Key Biodiversity Area, Priority Area, protected area, or forest block) which is potentially prospective for primary gem deposits. Most localities in the north and east of the island have potential for gems to occur in at least 5% of their area. 14 Key Biodiversity Areas (6%), 158 Priority Areas (12%), 11 protected areas (10%) and 304 forest blocks (7%) have potential for gems to be found in more than 75% of their area (Figs. 3 and 4). These localities are mostly small (median size = 135 ha). However, overall, most localities (over 50%) within each biodiversity layer, are not mapped as containing any potentially prospective geology (Fig. 4). For example, localities in the south-west and west which overlie Mesozoic sedimentary sequences have not been subject to the metamorphic conditions necessary for the formation of gems (Fig. 3 and Fig. S1) and are therefore not considered prospective for primary deposits (although some contain secondary deposits exploited by artisanal miners, eg. Zombitse-Vohibasia National Park and Amoron'I Onilahy Protected Landscape).

Our results are supported by the data on the 69 known gem deposits (both primary and secondary). Including a 500 m buffer zone, there are 11 (16%) known deposits within Key Biodiversity Areas, 11 (16%) within Priority Areas, 8 (12%) within protected areas (the Coridor Ankeniheny-Zahamena, Zahamena National Park, Ankarana Special Reserve, Zombitse-Vohibasia National Park, and Amoron'I Onilahy Protected Landscape), and 11 (16%) within a forest (although many of these deposits occur within multiple overlapping biodiversity features; Fig. S3).

4. Discussion

This study has revealed areas of potential future conflict between artisanal and small-scale gem mining and biodiversity conservation in Madagascar, but also opportunities for co-existence. Our results show that 11–14% of the most important area for biodiversity on the island could potentially host primary gem deposits and therefore be impacted by gem mining in future. This has global significance as high rates of endemism in Madagascar combined with the very restricted ranges of some species (Goodman, 2022) means habitat loss or degradation from mining could potentially lead to species extinction. However, we also show that 80% of the potentially prospective land (7 million hectares) lies *outside* these important areas for biodiversity, where the environmental trade-offs of gem mining could be minimised.

First, we explore how our approach could inform efforts to formalise ASM in countries with a nascent or growing sector through the establishment of designated zones for ASM. We then explore how this could apply within the legal and political context of Madagascar. Next, we consider the conditions which would be needed for legalised ASM within protected areas to be managed effectively. We finish by discussing the limitations of this study and potential avenues for future research.

4.1. *Informing the establishment of designated zones for ASM*

Our methods can be used to identify areas with the potential to host primary gem deposits *outside* of important areas for biodiversity. The top-down identification of *potentially* prospective areas, which contain the right geological conditions for the mineralisation of gems, can be used to target more detailed geological analysis and on-the-ground geological exploration to identify zones within these areas which are truly prospective (i.e. likely to contain primary gem deposits). This could inform efforts to formalise ASM through the establishment of designated zones where licensed ASM can be promoted and supported (Corbett et al., 2017), while minimising impacts on biodiversity.

Formalisation, bringing informal ASM into the legal economy, has emerged as a core policy response to the challenges of ASM (Hilson and McQuilken, 2014). Legalising ASM can enable better regulation, taxation, and improved environmental performance as license holders can be required to conduct environmental impact assessments or site remediation (Hilson et al., 2017; but see Álvarez-Berríos et al., 2021). It can also facilitate access to credit and technical support for miners, enabling investment in labour or technology to increase production and improve health and safety practices (Siegel and Veiga, 2009; Nopeia et al., 2022). In some countries (e.g. DRC, Mozambique) ASM is only legal within certain designated zones for miners in possession of a license (Hilson, 2020). However, these zones are often not defined on any geological

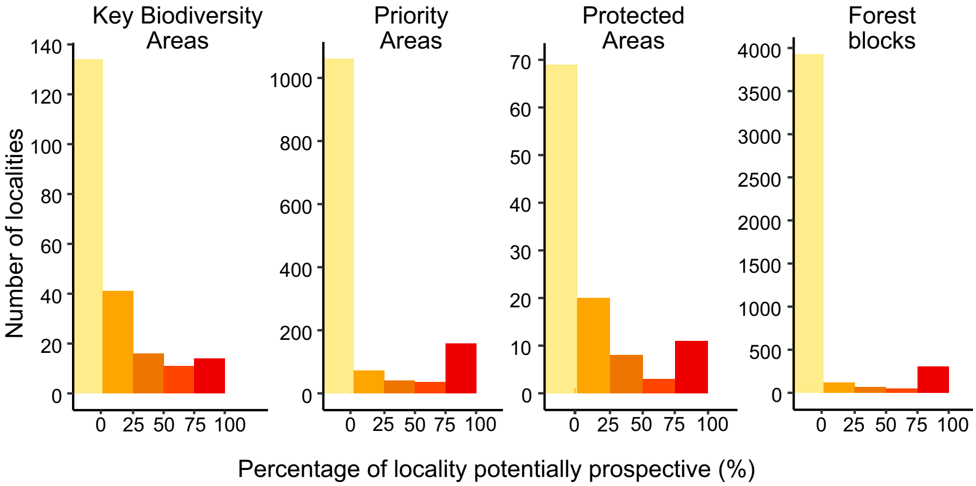

Fig. 4. Histogram shows the number of localities within each biodiversity layer grouped according to the percentage of the locality which is potentially prospective for primary gem deposits. Pale yellow bars represent the number of localities which do not contain any potentially prospective land. Forest blocks are only those larger than 84 ha (Supplementary Methods).

basis and therefore may not contain any workable economic mineral deposits (Dondeyne et al., 2009; Geenen, 2012). It is essential that any designation of ASM zones is grounded in the geology, to ensure that zones are truly prospective for the relevant minerals (Corbett et al., 2017; Hilson, 2020).

There are considerable political and practical barriers which need to be overcome for ASM to be formalised generally, and within designated zones. There is often a lack of political will to formalize ASM (Corbett et al., 2017; Hilson et al., 2017) rooted in a bias towards large-scale mining, elite vested interests, outdated discourses about the characteristics of artisanal miners, and a lack of understanding of the importance of ASM for rural livelihoods (Duffy, 2007; Geenen, 2012; Hilson et al., 2017; Vuola, 2022). A lack of political capacity to enforce the regulations is exacerbated by the remote location of much ASM and centralised governance structures (Geenen, 2012; Corbett et al., 2017; Hilson, 2020), and by inappropriate regulations (Hilson et al., 2017). Many formalisation efforts have failed because the duration and size of license squares do not reflect the nature of the deposits or the often transient, part-time nature of ASM (Dondeyne et al., 2009; Siegel and Veiga, 2009; Hirons, 2020). Additionally, there are practical challenges in demarcating designated zones for ASM amidst existing land claims, both formal and customary (Corbett et al., 2017; Álvarez-Berríos et al., 2021). In many countries where ASM is an important contributor to livelihoods, little land is truly unowned and unoccupied, and state attempts to acquire land for designated ASM zones could amount to further enclosure of the commons (Alden Wily, 2014; Mitchell, 2016). Finally, miners are typically risk-adverse and therefore must believe that the benefits of formalisation will outweigh the costs (Siegel and Veiga, 2009). Miners may be more willing to obtain a license and operate within designated zones if they know the area is likely to contain gemstones (Nopeia et al., 2022).

4.2. Establishing designated zones for ASM in Madagascar

Mining in Madagascar is regulated by the Mining Code of 2005, although a revised Code has recently been approved by the National Assembly and is proceeding through the courts but has not yet been promulgated (L'Express de Madagascar, 2023)). The revised Code includes a new provision for the creation of artisanal mining zones (in addition to existing permits for artisanal miners which can cover mining squares up to 50km^2; *Code Minier,* 2023). These zones are to be proposed by decentralised authorities and approved by the Minister of Mines. Artisanal miners wishing to work within these zones must form a collective and obtain an authorisation permit (*Autorisation minière d'exploitation artisanale)* which is valid for 6 months and renewable once (*Code Minier,* 2023). Similar provisions permitting the creation of gold panning corridors have been in force since 2005 (*Code Minier,* 2005). However, a recent a court audit found that no panning corridors have been established in Madagascar's main gold mining region (Cour des Comptes, 2022). Unfortunately, poor governance and capacity shortfalls severely limit the application and enforcement of the Mining Code in practice.

In the absence of the state, communities have established a variety of novel governance regimes, often drawing on customary arrangements, to regulate and govern ASM (Klein, 2022a, 2022b). In some cases, this has improved health and safety, community cohesion, benefit-sharing and mitigated environmental impacts (Klein, 2022a; Cook and Healy, 2012; Baker-Médard, 2012, cf. Canavesio, 2009). For example, in Soabiby in south-west Madagascar the local community was able to impose respect for local rules and customs on thousands of migrant sapphire miners, preventing mining within sacred forest areas and enabling land-owners to extract rents from miners (Baker-Médard, 2012). Given the current inability of the state to regulate ASM and broad distrust of state institutions (Walsh, 2003; Klein, 2022b), a decentralised, community-based approach towards establishing and managing designated zones for ASM could prove more effective, better at reconciling with existing land claims, and consequently more socially acceptable (Corbett et al., 2017; Hilson, 2020; Klein, 2022a, 2022b).

Designated zones for ASM may be best suited to establishing new, or formalising existing, long-term mining sites in Madagascar. They may struggle to provide strong enough incentives to discourage the 'rush type' mining common in Madagascar (Cartier, 2009), or mining in Protected Areas. Especially as Protected Areas are sometimes targeted for ASM in active resistance against the perceived appropriation of resources (minerals) by state/conservation interests, and the history of exclusion (Baker-Médard, 2012; Klein, 2022b).

4.3. The conditions needed for ASM within protected areas to be managed effectively

ASM within protected areas is illegal in many countries, including Madagascar (*Code Minier,* 2005; IGF, 2017). Yet, efforts to keep ASM out of protected areas, often involving the police or military, have often failed (Dondeyne et al., 2009; Villegas et al., 2012). In the worse cases, the resulting conflict has threatened lives (Baker-Médard, 2012; Gerety, 2017). Allowing a small amount of tightly-regulated ASM by license holders within sustainable use zones of a protected area has been attempted as an approach to address the impact caused by unregulated ASM within protected areas (e.g. in Gabon, Villegas et al., 2012; Hollestelle et al., 2012, and Daraina, Madagascar, Cook and Healy 2012). This approach could also help mitigate the impact of conservation restrictions and land enclosures on local livelihoods (Vuola, 2022).

However, effective management and regulation of ASM within protected areas requires strong rule of law, good governance, and effective, non-corrupt policing to monitor and enforce rules (Álvarez-Berríos et al., 2021). Without these foundations, which are lacking in many ASM hotspots (including Madagascar; IGF, 2017), permitting ASM within protected areas risks creating an open-access situation, leading to uncontrolled mining and environmental damage, jeopardising conservation goals (Villegas et al., 2012). Outcomes of efforts so far to regulate ASM within protected areas have been mixed. An influx of migrant miners caused the failure of the agreement in Gabon (Hollestelle, 2012). In Daraina, Madagascar, efforts of the conservation NGO Fanamby to regulate artisanal gold mining within the Loky-Manambato protected area have met with varying success and faced considerable challenges (Fanamby, 2021), including from rising insecurity during the political crisis of 2009 (Cook and Healy, 2012). In places without the capacity to prevent, or strictly manage, mining within protected areas, formalizing ASM outside of protected areas is the best solution (although this still requires considerable governance capacity).

4.4. Limitations of the study

The strength of our results rests on the quality of the data. The Geological Map of Madagascar (Roig et al., 2012) is a relatively broad scale (1:1,000,000) generalisation of more detailed mapping, which was itself constrained by the limited amount and accessibility of bedrock exposure across much of Madagascar. Consequently, there is uncertainty in the location of boundaries between geological units and the map cannot capture small-scale variation, meaning we were unable to capture small areas of gem potential (<1 km) within larger non-prospective units. We were unable to map the potential distribution of secondary deposits as maps of alluvial sediments are not available at a consistent scale across Madagascar. This is an important limitation, given that some of the largest gem rushes exploited secondary deposits. Finally, it was not possible to map the potential spread of gold deposits with the existing data available. Yet artisanal gold mining is widespread in Madagascar, including within Protected Areas, and is a source of conflict between mining and conservation (Cook and Healy, 2012; Cabeza et al., 2019). These limitations highlight the need for accessible, detailed geological data to underpin policy decisions.

None of the biodiversity datasets used in this study perfectly captures the distribution of Madagascar's biodiversity, and there will still be valuable biodiversity outside of these areas. However, using four datasets allows us to capture a variety of species and habitats and, by combining them, identify the areas of highest biodiversity value where the trade-offs from mining would be greatest.

4.5. Future research priorities

To date, there have been no robust, quantitative evaluations of the impacts of ASM on biodiversity in Madagascar. This needs to be addressed to ensure policy responses to ASM, particularly within protected areas, are appropriate and proportionate. A better understanding of local ASM governance is also needed to ensure formalisation policies are tailored to fit the context (Siegel and Veiga, 2009; Klein, 2022a).

5. Conclusion

ASM supports an estimated 45 million people within 80 low- and middle-income countries (World Bank, 2020). It is also a significant source of minerals, supplying 20% of global gold, up to 30% of cobalt, and 80% of the world's sapphires (World Bank, 2020). Yet ASM's positive contributions to development and mineral supply can involve substantial environmental trade-offs, impacting some of the most biodiverse regions on earth. Our approach could be applied in other biodiversity hotspots with a nascent or growing ASM sector to identify potentially prospective areas outside important areas for biodiversity where ASM could be promoted and supported. Policies to encourage ASM within designated zones of known mineral potential, but low biodiversity, could help to mitigate conflicts between mining and conservation, facilitate distribution of financial and technical support to improve practices, and contribute towards formalisation of the sector.

Data availability

The database of known gem deposits compiled in this study is available here: https://github.com/katie-devs

Acknowledgements

We are grateful to Jorge Llopis for sharing the edited protected areas dataset and Vincent Pardieu for sharing the GPS locations of the many gem mining sites he has visited in Madagascar. This work was funded by the Natural Environmental Research Council Envision DTP.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.exis.2023.101311.

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